UPC 073

Fermilab

A Scenario to Achieve a Luminosity of Approximately 5 x 10^{29} cm^{-2} sec^{-1} for $p\bar{p}$ Collisions in the Fermilab Energy Doubler

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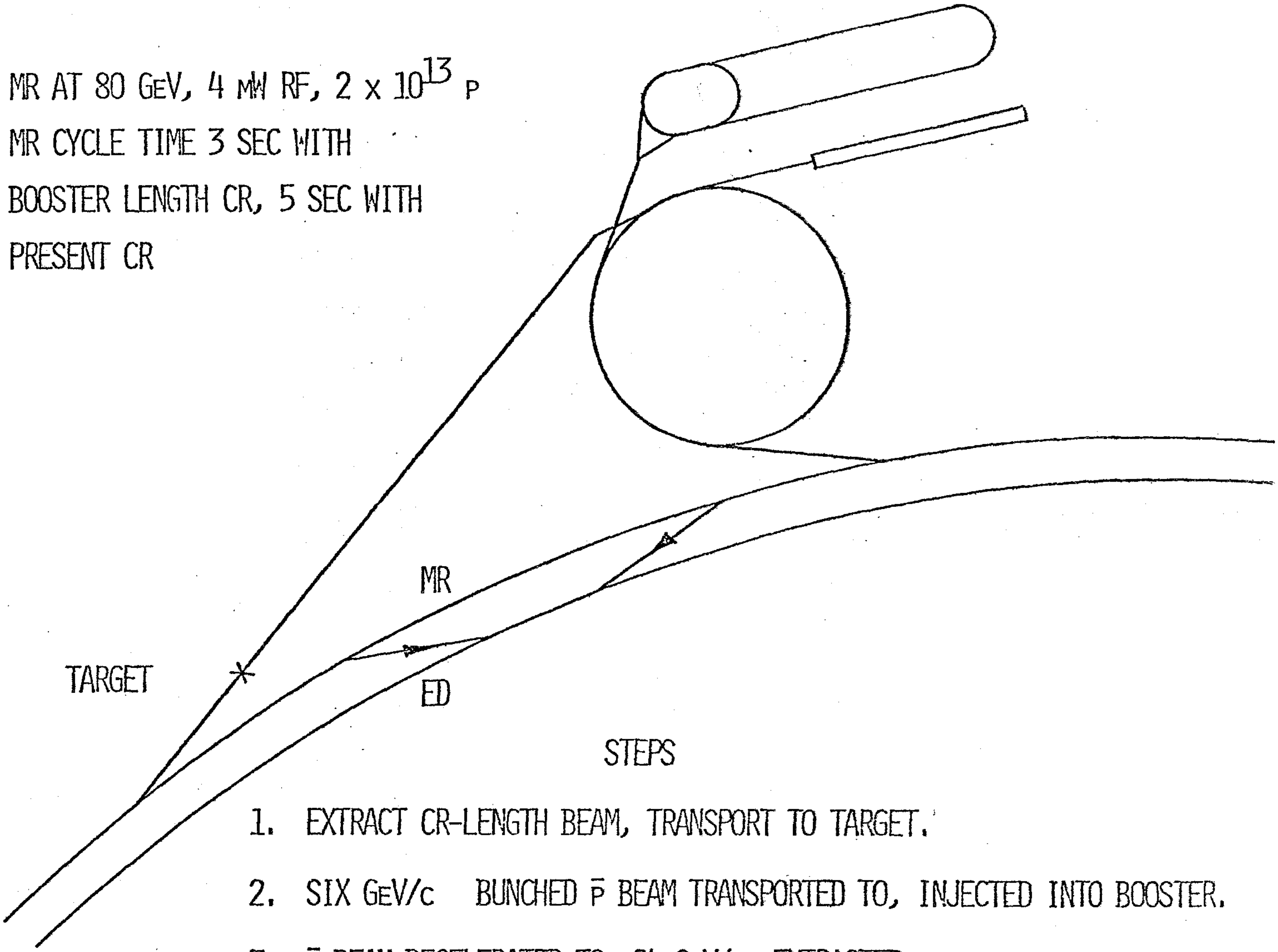
Abstract

The following notes describe a scenario for collecting antiprotons by targeting an 80-GeV proton beam from the main ring, accumulating and cooling these antiprotons in the electron cooling ring, and accelerating these antiprotons (and protons) for 1 TeV collisions in the energy doubler. A basic luminosity calculation (considered a minimal luminosity before improvements) is calculated and compared with the collision scheme proposed by CERN (in the SPS) according to Berley and Month[1]. Improvements to this scenario are described that would result in a luminosity of approximately 5 x 10^{29} cm^{-2} sec^{-1} if all of the factors could be realized.

1. D. Berley and M. Month, "Luminosities of Proton - Antiproton Colliding Beams" Proceedings of the Workshop on Producing High Energy Proton-Antiproton Collisions" March 27-31, 1978 (Fermilab -- to be published).

COLLECTING ANTIPROTONS

MR AT 80 GeV, 4 MW RF, 2×10^{13} P
MR CYCLE TIME 3 SEC WITH
BOOSTER LENGTH CR, 5 SEC WITH
PRESENT CR



STEPS

1. EXTRACT CR-LENGTH BEAM, TRANSPORT TO TARGET.
2. SIX GeV/c BUNCHED $\bar{p}$ BEAM TRANSPORTED TO, INJECTED INTO BOOSTER.
3. $\bar{p}$ BEAM DECELERATED TO .64 GeV/c, EXTRACTED.
4. TRANSPORT $\bar{p}$ TO CR, INJECT.
5. RF STACK $\bar{p}$ AT COOLING ENERGY.
6. REPEAT UNTIL ALL MR PROTONS ARE USED.
7. RECYCLE MR, REPEAT 1 - 6.

Figure 1

Antiproton Collection

$$N_{\bar{p}}/N_p = \frac{1}{\sigma_{abs}} \; E\frac{d^3\sigma}{dp^3} \; \frac{dp_\perp^2 \, dp_\parallel}{E} \; \varepsilon_T$$

$$dp_\perp^2 = 4p^2 \, \theta_x \theta_y$$

$$\theta_x = \sqrt{\frac{\varepsilon_x}{\pi\beta^*}} \qquad \theta_y = \sqrt{\frac{\varepsilon_y}{\pi\beta^*}}$$

ε_T includes
p absorption
$\bar{p}$ absorption
depth of focus
chromatic aberration

Design by G. Chadwick

gives $\beta^* = 2\,cm \quad \varepsilon_T = .15$

Booster Acceptance $\quad \varepsilon_x = 2.8\pi \times 10^{-6} m$
$\varepsilon_y = 1.4\pi \times 10^{-6} m$
$\Delta p/p = 2.6 \times 10^{-3}$

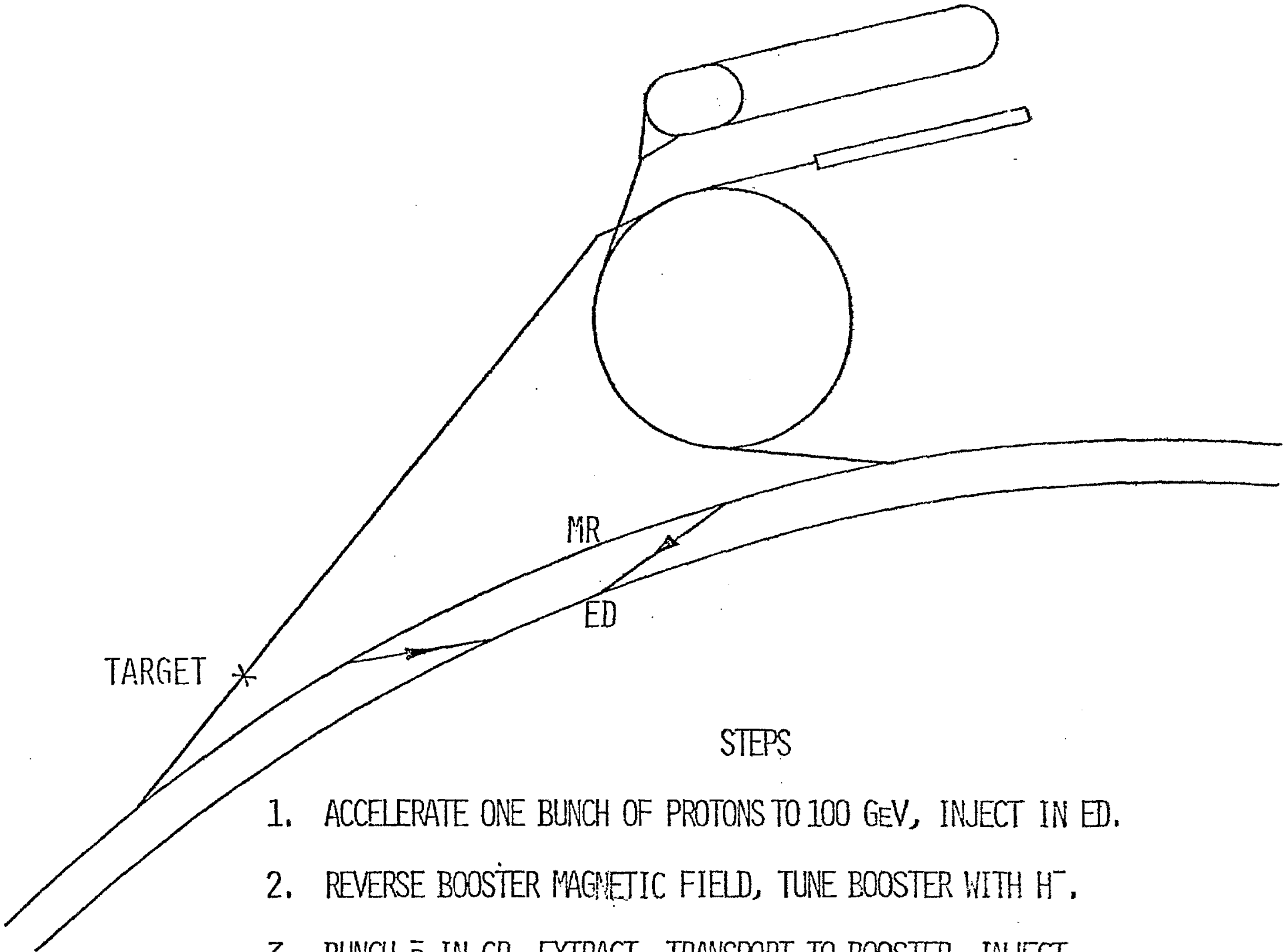
For $\sigma_{abs} = 40\,mb$

$$E\frac{d^3\sigma}{dp^3} = 0.6\ mb/Gev^2 \quad , \quad N_{\bar{p}}/N_p = 0.83 \times 10^{-7}$$

$$\frac{dN_p}{dt} = 2.4 \times 10^{16}\ p/hr \qquad \frac{dN_{\bar{p}}}{dt} = 2 \times 10^{9}\ \bar{p}/hr$$

Figure 2

COLLIDING p WITH $\bar{p}$ AFTER ACCUMULATION



STEPS

1. ACCELERATE ONE BUNCH OF PROTONS TO 100 GeV, INJECT IN ED.
2. REVERSE BOOSTER MAGNETIC FIELD, TUNE BOOSTER WITH H^-.
3. BUNCH $\bar{p}$ IN CR, EXTRACT, TRANSPORT TO BOOSTER, INJECT.
4. ACCELERATE $\bar{p}$ TO 8 GeV, EXTRACT, REVERSE INJECT IN MR.
5. ACCELERATE TO 100 GeV, EXTRACT, INJECT IN ED.
6. ACCELERATE TO COLLIDING ENERGY.

Figure 3

Colliding at 1 Tev

$$L = \frac{4 N_p N_{\bar{p}} f}{N_B \sqrt{\beta_x \beta_y (\varepsilon_{px} + \varepsilon_{\bar{p}x})(\varepsilon_{py} + \varepsilon_{\bar{p}y})}}$$

Gaussian beams, ε includes 98% of beam

Emittance: 10^{13} p at 400 Gev : Gaussian, $\varepsilon = .05\pi \times 10^{-6}$ m for 98% of beam. At 2×10^{13}, ε increases by 30%. (Ohnuma)

1 Tev p's $\varepsilon_{x,y} = \frac{400}{1000} \times 5\pi \times 10^{-8} \times 1.3 = 2.6 \times 10^{-8} \pi$ m

$N_p = 2\times10^{10}$, $N_{\bar{p}} = 8\times10^{9}$, $\sqrt{\beta_x \times \beta_y} = 2.5$ m

$\varepsilon_{\bar{p}} = \frac{N_{\bar{p}}}{N_p} \varepsilon_p = 0.8 \times 10^{-8} \pi$ m

$f = 4.8 \times 10^{4}$ Hz

$L \cong 10^{28}$ cm^{-2} sec^{-2}

Figure 4

TABLE I - Luminosity Comparison

Production	Fermilab	CERN
Proton Energy (GeV)	80	26
Protons/sec	6.7×10^{12}	3.8×10^{12}
$\bar{p}$ Momentum (GeV/c)	6	3.5
$\Delta P/P$	2.6×10^{-3}	15×10^{-3}
Acceptance (mm-mrad)	$2.8\pi \times 1.4\pi$	$100\pi \times 100\pi$
Production angle (mrad)	12	67
β^* (target) (cm)	2	2.3
$(Ed^3\sigma/d\bar{p}^3)$ (mb/GeV^2)	0.6	0.2
Target efficiency (ε_T)	0.15	0.15
$N_{\bar{p}}/N_p$	8.3×10^{-8}	190×10^{-8}
$N_{\bar{p}}$/sec	5.5×10^5	72×10^5
$N_{\bar{p}}$/hr	2.0×10^9	26×10^9
Colliding Beams		
Energy (GeV)	1000	270
N_p	2×10^{10}	6×10^{11}
$N_{\bar{p}}$	6×10^9 (3 hrs)	6×10^{11} (24 hrs
N_B	1	6
$\sqrt{\beta_x \beta_y}$ (m)	2.5	2.2
ε_{HP} (m-rad)	$2.6\pi \times 10^{-8}$	$6.9\pi \times 10^{-8}$
ε_{VP} (m-rad)	$2.6\pi \times 10^{-8}$	$3.5\pi \times 10^{-8}$
$\varepsilon_{H\bar{p}}$ (m-rad)	$0.8\pi \times 10^{-8}$	$3.8\pi \times 10^{-8}$
$\varepsilon_{V\bar{p}}$ (m-rad)	$0.8\pi \times 10^{-8}$	$1.9\pi \times 10^{-8}$
$\mathcal{L}$ (cm^{-2}-sec^{-1})	10^{28}	10^{30}

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POSSIBLE $\bar{P}P$ IMPROVEMENTS

(To Present Scenario with $\mathcal{L} \approx 10^{28}$ cm^{-2} sec^{-1})

IMPROVEMENT	POSSIBLE $\mathcal{L}$ FACTOR
1. Main Ring Intensity ($2 \times 10^{13} \rightarrow 3 \times 10^{13}$)	1.5 - 2.25
2. RF Rebunching, Main Ring ($2 \times 10^{10} \rightarrow 10^{11}$ ppb)	5
3. Low β^* Insertion (2.5 m → 1.4 or 1.9 m)	1.5 - 1.8
4. Targetry	2
5. Booster Acceptance	
A. Momentum phase space.	1.5
B. Betatron phase space.	—
C. Cooling at higher energy	1.5
	$\mathcal{L}$ X 50

1. Main Ring Intensity Improvement

The booster has been the intensity limiting system at Fermilab for several years. Recently the booster has set a new intensity record of 3×10^{12} ppp, leading to 3.9×10^{13} protons injected into the main ring. It is to be expected that the main ring, whose present record is 2.5×10^{13}, will be able to use more protons and achieve 3×10^{13} ppp. This is 50% more than assumed in the luminosity calculation. This should allow a factor of 1.5 increase in the number of protons per bunch in collision, and increase the rate of accumulation of $\bar{p}$ by a factor of 1.5. Depending in detail on the scenario, that is the number of $\bar{p}$ bunches, number of $\bar{p}$'s per bunch, the blow-up of proton emittance, etc., the luminosity increase should be between 1.5 and 2.25.

2. Main Ring Rebunching

At 100 GeV in the main ring with 1.2 MV rf voltage, the ratio of rf bucket area to beam area is about 100. If, say, five bunches were compressed into one bucket with 100% dilution, then, still only 10% of that bucket area would be full, but the bunch would be five nano seconds long.

The most straight forward method to achieve this is to (1) debunch the main ring beam as well as possible (2) turn on a 1 MHz cavity to modulate the energy of the beam (3) drift the beam until it is bunched, (4) recapture the bunches with the main rf system. The beam can be "scraped" by lowering the voltage and accelerating or decelerating the beam somewhat.

The limitations on the number of protons in one bunch arise from transverse and longitudinal (microwave) instabilities. The transverse instabilities can be controlled by establishing the correct (slightly positive) chromaticity, together with feedback (the present system is sufficient). The microwave instability can be controlled by the use of a high frequency cavity to modify the longitudinal rf potential well to increase the spread of synchrotron oscillation frequencies in the bunch. This method has worked well in SPEAR, and experiments are presently being mounted in the main ring. We hope to be able to obtain 10^{11} protons in several main ring buckets, corresponding to five normal MR bunches compressed into one. This would yield a luminosity increase of five.

3. Low β Insertion

The present design for the low β insertion[2] calls for $\sqrt{\beta_x^* \beta_y^*} = 2.5\,\mathrm{m}$, and finite momentum dispersion, leaving room for dipole magnets to bring main ring and doubler beams together. Other studies[3] have investigated the case where more of the straight section can be used for quadrupoles (1) to achieve a lower β^*, (2) to reduce the maximum value of β, and (3) to remove momentum dispersion in the intersection region and to reduce it elsewhere. At Aspen, Guingnard found solutions for $\sqrt{\beta_x^* \beta_y^*} = 1.9$ m. Subsequently the CERN group[4] has adopted for the SPS collider an insertion using conventional magnets with $\sqrt{\beta_x^* \beta_y^*} = 1.4$ m. Using superconducting magnets in the doubler should lead to comparable performance, leading to a luminosity increase of 1.5 - 1.8.

2. TM-737, D. Johnson.

3. G. Guignard, 1977 Aspen Summer Studies

4. S. Vander Meer private communication.

4. Targetry Improvements

The presently designed $\bar{p}$ collection system employs a quadrupole triplet. The expected performance of the system[5] is given in Table II.

TABLE II

$\bar{p}$ momentum	6.0 GeV/c
Proton beam diameter	0.5 mm
Collection angles	12 mrad x 8.5 mrad
β ($\bar{p}$ at target)	2 cm
Emittance (10^{-6}) m-rad	2.8 π x 1.4 π
Momentum spread	.0026
ε_T	.15

The numbers in Table I correspond to booster acceptances. The line itself will transport somewhat larger beams, of 4 π emittance and $\Delta p/p \sim .8\%$.

The performance of the system is dominated by its short depth of focus. Away from the focus, the angular acceptance varies approximately as

$$\Theta = 2\Theta_1 \frac{s/\beta_1}{1+(s/\beta_1)^2}$$

and is smaller for $s>\beta_1$. Here $\pm\ \Theta_1$, is the angular acceptance at the focus. The situation is as shown in figure 5. One tries to compensate for the depth of focus problem by using short high Z targets. This leads to heating problems (990^o in the core of the beam for the Chadwick Design). Chromatic aberration is not serious in the

5. G.B. Chadwick, "Antiproton Production Beam and Reverse Injection System", Ferilab Design Report, April, 1978 (to be published).

present design, because in first approximation the effect of differing momentum is simply to move the point at which the waist occurs to a different point in the target.

Improvements in targetry should be aimed at; (1) improving the depth of focus to allow collection over a larger fraction of an absorption length and use of lower Z targets, and (2) increased solid angle within the same emittance (lower β_1).

The depth of focus problem can be solved by keeping β constant (magnetic focusing) inside the target, as indicated in figure 6. The current required to contain a beam with a maximum random angle Θ is*

$$I = \frac{I_o\ (\beta\gamma)}{2}\ \Theta^2 ; \quad I_o = \frac{mc^3}{e} = 3.14 \times 10^7 \text{ A}$$

For the design case Θ = 12 mrad and I = 15 kA, that is, the current which must flow within the 0.5 mm diameter beam is 15 kA. This appears to be roughly in line with present capabilities (10^6 A in 1 cm diameter, pressure limited). If this is indeed possible, then the targets can be extended to their optimum lengths and the target efficiency can be doubled (and lower Z targets can be used).

If higher current density can be used, then the collection angle Θ can be increased, and a larger number of antiprotons can be captured in the same emittance. In this case, a horn may be a better solution than the quad triplet as the first focal element after the target. The CERN design uses a horn to capture ~50 mrad, in $\varepsilon = 100\ \pi \times 10^{-6}$ m-rad (β~2 cm).

*This is the same relationship as for a neutralized beam of current I.

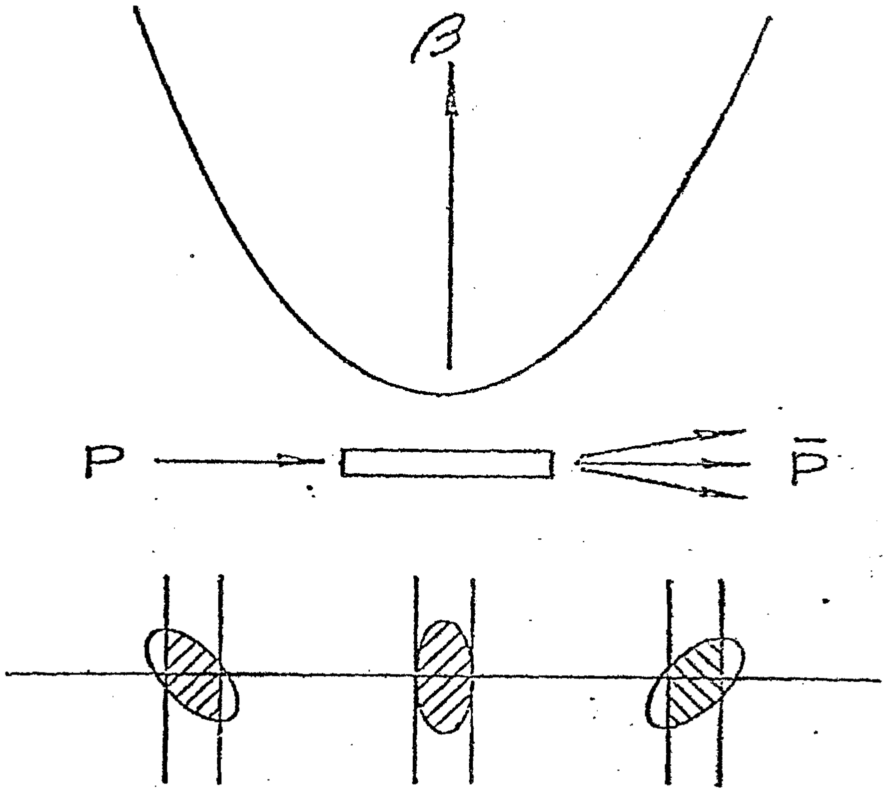

Figure 5

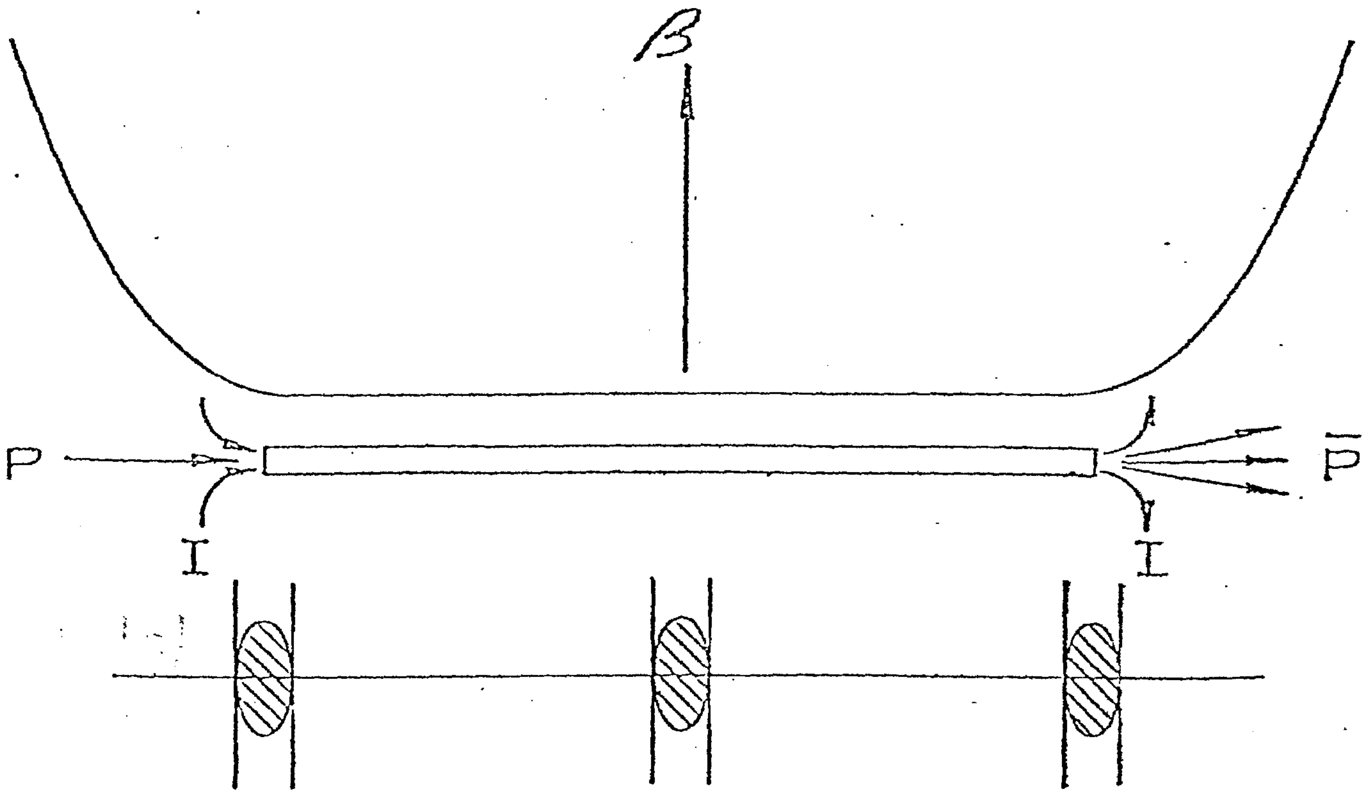

Figure 6

5. Booster Acceptance

A. Momentum

The booster 85th harmonic longitudinal phase space ellipses at 6 GeV/c which can be decelerated to 200 MeV (2 eV-sec for 85 bunches) are wider in time than the bunches from the main ring. Moving transition energy will narrow the booster ellipses in time and enlarge their momentum width, allowing capture of more $\bar{p}$'s, see Fig. 7. The main ring bunches should be maximally compressed, i.e. rf voltage maintained at 4 MV during extraction and targetry interval. Further compression can be obtained (~15%) by using the high frequency (470 MHz) cavity.

Another scheme is currently under study[6], using the 86th harmonic to decelerate the $\bar{p}$'s. The $\bar{p}$ collection momentum is 4.3 GeV/c. The velocity difference between this momentum and .65 GeV/c is less than from 6 GeV/c. Then the booster rf can always operate at higher frequencies, where the available rf voltage is higher, allowing more longitudinal phase space acceptance (higher $\Delta p/p$). Further, it is easier to reduce the transition energy than raise it. The transverse acceptances are higher (less adiabatic undamping) yielding a larger solid angle. The principal uncertainty is in the knowledge of the production cross section. This will result in an increase in the number of $\bar{p}$'s collected per unit of time and a luminosity increase of a factor of 1.5.

B. Betatron phase space

The present booster betatron acceptance, used in the $\bar{p}$ collection estimates, is taken to be 26π, $13\pi \times 10^{-6}$ mrad, which is the acceptance for a high intensity space-charge limited beam. The space charge mechanism (tune modulation as the particles circulate in the bunch) is most destructive for large oscillation amplitudes. The booster acceptance for a low density beam could be substantially more, at least for

6. C. Hojvat, Private Communication.

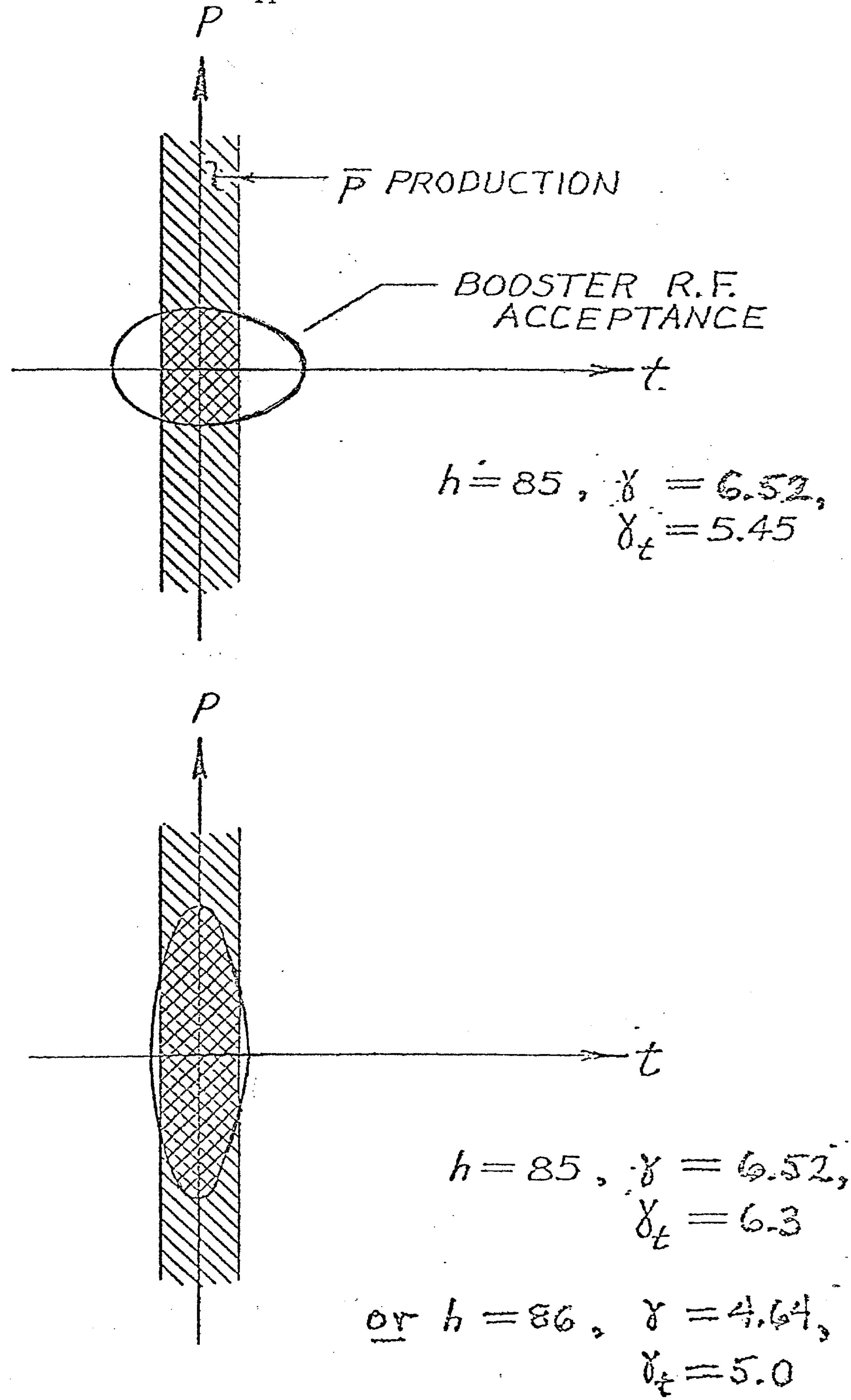
P
$\bar{P}$ PRODUCTION
BOOSTER R.F. ACCEPTANCE
t
$h \doteq 85$, $\gamma = 6.52$, $\gamma_t = 5.45$
P
t
$h = 85$, $\gamma = 6.52$, $\gamma_t = 6.3$
or $h = 86$, $\gamma = 4.64$, $\gamma_t = 5.0$

Figure 7

the radial motion.

Operation of a vertical dogleg around the extraction septum could allow an increase in vertical acceptance as well. Experiments need to be done to measure the acceptance with a low intensity beam to see of one can approach the geometrical acceptances of ~40π, $20\pi \times 10^{-6}$ mrad. The increase in $\bar{p}$ collection because of this increase in booster aperture is unknown and no increase in the luminosity has been taken even though an improvement is expected.

C. Cooling at higher energy.

The cooling ring magnet system and cooling system can operate at 50% higher momentum. If acceptable cooling rates can be achieved at this momentum., then transfer from the booster could be made at this energy. This allows larger solid angle of $\bar{p}$ collection because of less adiabatic damping. Again, somewhat more rf voltage should be available. The gain in collection rate could be greater than a factor of 1.5.